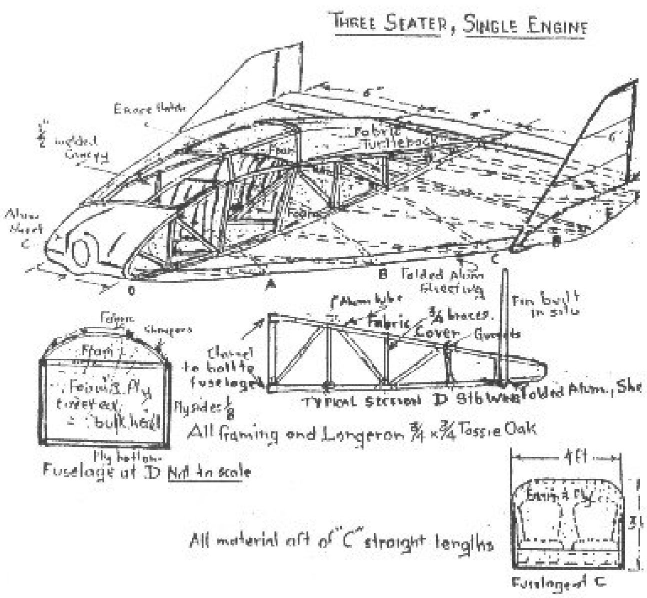
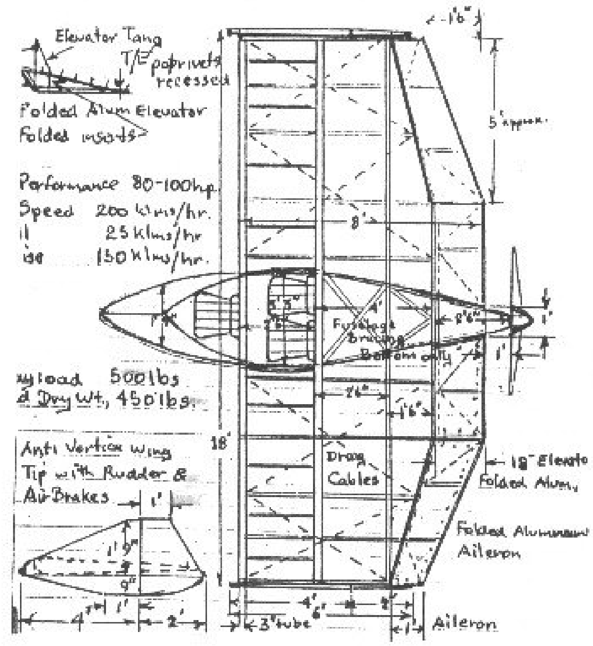
No. 162 DECEMBER 1999

T.W.I.T.T. NEWSLETTER





Two concepts by Terry (The Tiger) Baxter, our newest member from Australia. See more in next month's newsletter.

T.W.I.T.T.
The Wing Is The Thing
P.O. Box 20430
El Cajon, CA 92021

The number after your name indicates the ending year and month of your current subscription, i.e., **9912** means this is your last issue unless renewed.

Next TWITT meeting: Saturday, January 15, 2000, beginning at 1:30 pm at hanger A-4, Gillespie Field, El Cajon, CA (first hanger row on Joe Crosson Drive - Southeast side of Gillespie).

TWITT

THE WING IS THE THING

THE WING IS THE THING
(T.W.I.T.T.)

T.W.I.T.T. is a non-profit organization whose membership seeks to promote the research and development of flying wings and other tailless aircraft by providing a forum for the exchange of ideas and experiences on an international basis. T.W.I.T.T. is affiliated with The Hunsaker Foundation which is dedicated to furthering education and research in a variety of disciplines.

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Meetings are held on the third Saturday of every other month (beginning with January), at 1:30 PM, at Hanger A-4, Gillespie Field, El Cajon, California (first row of hangers on the south end of Joe Crosson Drive, east side of Gillespie).

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PRESIDENT'S CORNER

Now that I have something to work with from you comments, the next problem we face is continuing program material. This is not a new problem, but one that keeps coming up as we exhaust our sources for speakers. Although we have some speakers identified for later in the year 2000, it points out the difficulty of fitting a speaking engagement into someone's busy schedule.

So, I will make my periodic plea to our Southern California members to be on the lookout for potential speakers. This could even mean yourself if you have a unique idea for a flying wing and want feedback, or have some special building skill to share with others. The main thing to remember is that the subject should be as directly related to flying wings as possible.

For those of you in the electronic world, you probably haven't seen any changes to the web site lately. I apologize for that, but other committments have gotten in the way again, and limited the amount of time available for such things. Hopefully over the holidays I will have less work and professional group work taking up my time and be able to refresh some of the material on the web pages. I have found a lot of new links, so will probably be rearranging how that is done to save some space and make them easier to download with a standard modem connection.

Speaking of the holidays, I hope everyone will be able to enjoy time with their families and friends. It has been hard getting into the holiday spirit here in Southern California since the day time temperatures are still in the mid-seventies with clear skies. Even our mountains seem to be short of snow this year, but maybe by Christmas things will change.

MERRY CHRISTMAS
AND
HAPPY NEW YEAR

JANUARY 2000 PROGRAM

As of our publication date we didn't have a January program firmly lined up. We are working on one possibility, but we also need a backup program since the primary speaker is subject to short-notice by his employer. We will have something more definite for you in next month's newsletter, but make sure to mark your calendar for January 15, 2000, so you won't miss the meeting.

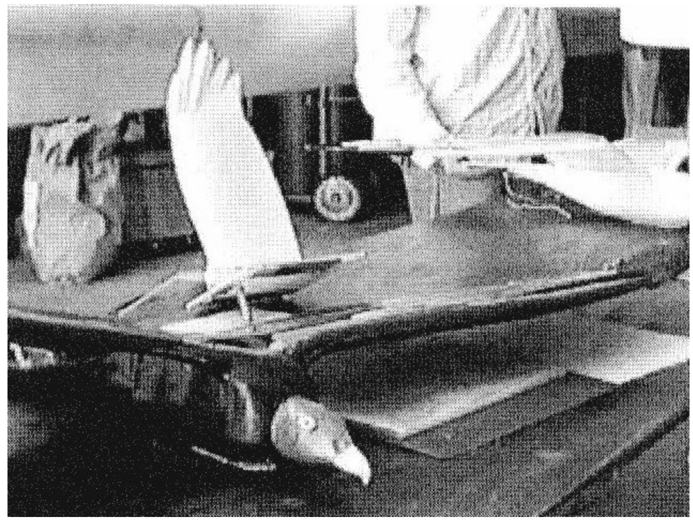
MINUTES OF THE NOVEMBER 20, 1999 MEETING

Andy opened the meeting by welcoming everyone to the last meeting of the millennium, at which time almost everyone said that wasn't coming for another year yet. What else could you expect for an audience of engineers, mathematicians and physicists? So Andy conceded and welcomed everyone to the last meeting of 1999. He then outlined the program for the day, which would include a short video taken from the History Channel, and then a two-part presentation by Bob Hoey on his team's simulated soaring bird flight models.

After everyone introduced themselves, especially since we had some first timers in the crowd, Andy showed the short video clip he was able to get off the History Channel a few months ago. It was sort of computer aided drawing program on the Horten flying wings and how some of them were developed during WW II. It was interesting and included some B&W film clips from the era. What seemed to surprise the Horten enthusiasts was the H XVIII, which was presented as a long-range bomber capable of delivering an atomic bomb on New York City and returning to Germany. Of course, Germany hadn't completed an atomic bomb and the H XVIII was never more than an idea on paper, but there didn't seem to be much known about it among our group. *(ed. - We have since learned there is some information in the Nurflügel book on this aircraft, but not a lot and definitely nothing concerning its use with an atomic bomb.)*

Andy mentioned he had received an e-mail from Phil Rendahl letting us know that a full size 54' span Horten wing was nearing completion in Red Bluff, CA. Apparently the builder visited with Dr. Horten while he was still alive which is where he got the plans and additional information. *(ed. - I got a later message from him with more details that is included in the Letters to the Editor section.)*

With the preliminaries out of the way Andy introduced Bob Hoey who would be telling us of his experiences with radio controlled Ravens, Buzzards and Sea Gulls while trying to duplicate the way wing tip feathers work. (ed. - The first part of Bob's presentation was taken from his AIAA paper published in 1992, since it covers the basics of the project. The second part, which will be published in the January newsletter, will be taken from the audio transcript of the meeting since it covers the next generation of actual tip feather simulation.)



ABOVE: This is a shot of the Buzzard in the foreground, with the water tunnel model directly behind it and, the seagull model at the rear of the table.

This research effort was undertaken to determine if birds are statically stable in soaring flight and to identify the control methods they use for initiating turns. Once man learned how to fly on his own terms, the rapidly evolving fields of aeronautics and aerodynamics focused on improving man's ability to fly, and interest in how the birds do it waned. Bob's background in stability and control flight-testing fostered an interest in bird flight, since, after all, they must abide by the same laws of physics as we do. Large soaring birds appear to be relatively passive while in soaring flight, so it was felt that this might be a good place to start. The specific objectives of the study were to:

1) Determine if soaring birds are statically stable in the lateral-directional axis and, if so, identify the stability source.

2) Determine if soaring birds are statically stable in the pitch mode.

3) Identify the aerodynamic method used by birds for controlling turns in soaring flight.

Since large birds are of the same general size and wing loading as a typical radio-controlled (R/C) model airplane, Bob reasoned that he should be able to construct and fly a full scale R/C glider model of a soaring bird. The Raven was chosen as the initial subject since they are plentiful in the California desert for photographing and observing, and since they soar with their wings essentially flat. A baseline configuration was established which was a composite of many telephoto and video pictures of these variable-geometry creatures. An actual Raven was weighed and measured and the model configuration was scaled to be about 8% larger than a real bird to allow for radio equipment in the fuselage. *(ed. - At the meeting, Bob mentioned that for some unknown reason a Raven collapsed and* *crashed to the ground in his area one day and this became the source of some of the measurements.)*

Early flights of the model were hand-launched from a gently sloping hill. A video camera was used to record different test results and to measure speeds and flight path. An air-launch technique was developed utilizing another R/C mothership (Sr. Telemaster). This was a key factor in the research effort allowing consistent and repeatable experiments to be performed. Testing proceeded by making small configuration changes and qualitatively observing differences in stability and controllability. Test maneuvers were generally step turn inputs for lateral control or speed changes using the elevator.

Prior to the first flights of an R/C Raven model, several small profile free flight models were built to test various control methods. The initial flights of these models showed, to Bob's surprise, that the configuration was statically stable in all axes. Longitudinal control was straight forward using the aft third of the tail as an elevator and adjusting CG position for stability. Lateral control was more of a challenge. All combinations of wing twisting methods such as ailerons, differential leading edge flaps, spoilers, full chord pivoting wing tips, etc., were tried. The results were fairly consistent. The small models would yaw and turn in the opposite direction to the applied roll control due to adverse yaw and dihedral effect. When a small vertical fin was added to these models the roll control devices behaved in their normal sense.

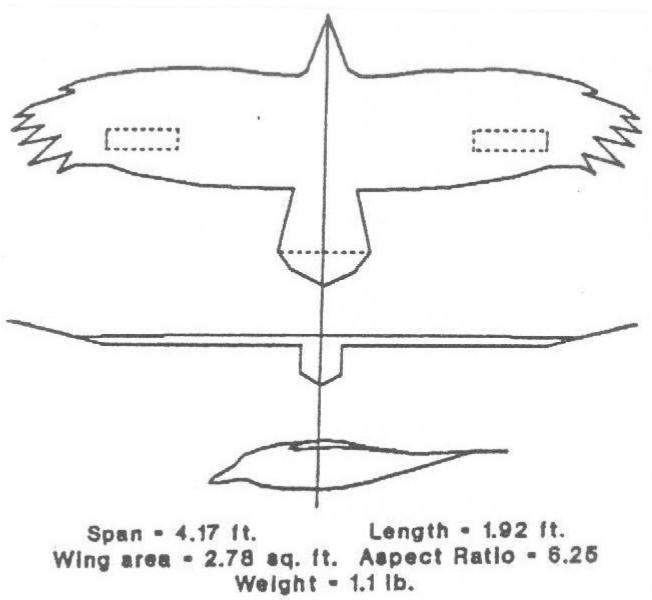


Fig. 1 Baseline Raven

It became obvious that if the larger R/C version was to be flown without a vertical tail it would have to be flown using a yaw-producing control device and dihedral effect for lateral control. The use of drag flaps, acting downward only, on the lower surface of each wing provided a yawing moment, which caused the model to turn in the direction of the deflected flap (the reverse of a normal aileron). This proved to be a consistent control scheme and was utilized for the baseline model.

The first flights of the full-scale R/C model showed positive static stability, but exhibited a neutrally damped lateral-directional oscillation with a period of 3.25 seconds. These oscillations were eventually eliminated by reducing the weight (and thus the roll and yaw inertia) of the wing structure which was initially built quite strong and heavy to survive expected crashes.

The fully developed baseline Raven model is quite easy to fly in spite of the lack of a vertical tail and has excellent turning capability. It has been thermalled frequently and has been joined by real Ravens and Hawks on several occasions. A typical flight is launched from an altitude of about 500'. In still air the flight time is about 3 minutes, however, thermalling flights often exceeded 30 minutes.

Layout of the baseline Raven model is shown in Fig. 1 along with pertinent dimensions. The moments of inertia were measured whenever major configuration changes were made. The model was suspended in a cradle from a fixed point about 3" above the CG. The frequency of the free oscillation was measured in each axis and the pendulum equations used to compute the inertias.

Control is provided through a 2 or 3 channel model airplane transmitter, receiver and servos. Along with the drag flaps mentioned earlier, two tail configurations have been flown. The first consisted of a simple elevator at the back of the tail feathers as shown in Fig. 1. The second was a more complex "rolling tail" mechanism which allowed the entire tail area aft of the wing to pivot up and down for pitch control and also rotate around a longitudinal axis for combined pitch and yaw control (Fig. 2). The rolling tail was flown primarily with the "cruise" wing as shown in Fig. 2. Over 300 air-launched flights were accomplished on three test articles over a year period.

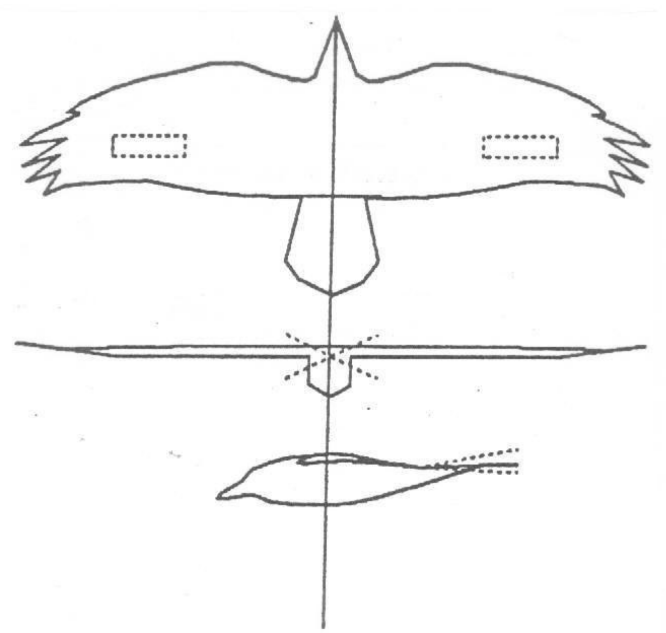


Fig. 2 Cruise3 configuration with rolling tail.

There were no specific performance objectives of this study since it was known that lift and drag measurements would be very difficult. In addition, there was only a cursory attempt to duplicate the thin, undercambered airfoil of a bird. Nevertheless, some differences in the flight characteristics of the model have been observed which are associated with different wing airfoils. The prototype airfoil was an angular, cambered airfoil with a small reflex near the trailing edge (Fig. 3). Initial flights showed a very narrow angle of attack range for this airfoil and a rapid "nodding" characteristic (small, neutrally damped pitch oscillation of about 2 Hz) when full aft stick was applied rather than a classical stall. Tuft studies were done by holding the model into the afternoon desert winds, and taking video photos of the tufted wing. The flow over the entire wing was observed to separate abruptly right at the leading edge. The coordinates of this airfoil were approximated using R.T Jones and R. McWilliams "Oshkosh Airfoil Program". The resulting pressure distributions are shown in Fig. 3 and show a sharp pressure spike developing at the leading edge at fairly low angles of attack; consistent with the tuft observations.

The computer program was then used to develop a second airfoil with a more gentle pressure distribution but with the same, positive pitching moment coefficient (Fig. 4, OSH4) (the Cm_{ac} for both airfoils was about +.03). With this airfoil the model had a wider speed range, a much-improved glide, but still exhibited the "nodding" stall characteristic, although both the frequency of the nodding and the airspeed at which it occurred were slower. This "nodding" stall characteristic has been observed on all configurations and CG positions flown and appears to be associated more with the planform than with the airfoil.

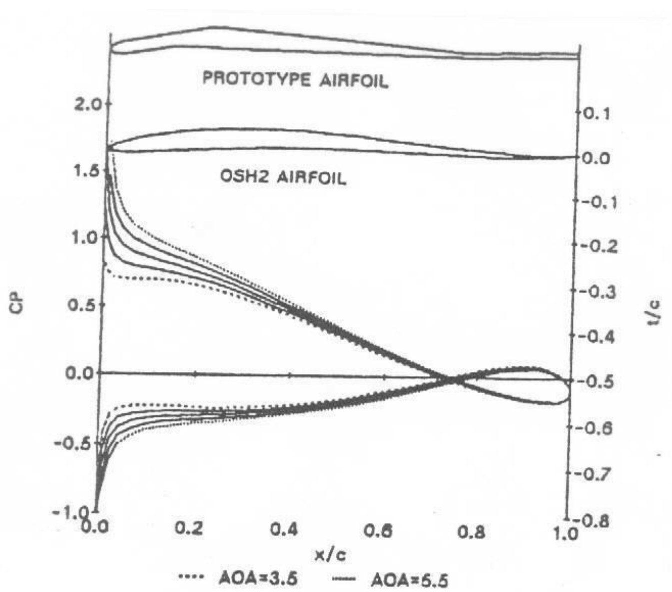


Fig. 3 Pressure Coefficient OSH2 airfoil.

An in-flight video was analyzed to determine flight speed. This was very time consuming and resulted in a very low confidence in the measurement, but it appeared the lift-to-drag ratio was about 8. Calculated lift coefficients are plotted versus angle of attack in Fig. 6 and compared with the OSH4 airfoil predictions corrected for aspect ratio. Correlation is not bad considering the instrumentation and test methodology. A sample time history of one of these analyses is shown in Fig. 5 for a flight with the OSH4 airfoil. Flight velocities are seen to be about 20 fps at an angle of attack of about 12º. For this particular landing full up-elevator was applied 1.7 seconds before landing and the "nodding" oscillation of about 2 Hz can be clearly seen in the angle of attack data.

The Raven model is quite short-coupled in the pitch axis and was treated during the design phase as a flying wing. The slightly reflexed airfoil was felt to be consistent with some slight flexing or unloading of the wing feathers at the trailing edge of a real bird. More importantly the reflex has allowed the model to be flown with the tail loaded both upward and downward as determined by the turn direction when the tail was tilted. Successful flights have been made with CG positions between 23% and 29.3% MAC. A CG position of 29.3% was obviously very close to the neutral point and required constant attention in flight to maintain a proper speed and attitude. Keep in mind that real birds don't really alter their CG. Instead, they utilize for and aft wing articulation for active and rapid control of the location of the wing lift vector and thus the static margin. If the airfoil of a real bird does not unload (or reflex) at the trailing edge as assumed here then the Cmac is negative and the bird must surely be flying with a slightly negative static margin if observations of an up-loaded tail are correct.

Flights have shown evidence of a persistent longitudinal phugoid oscillation, which is divergent for some configurations. It is most noticeable on the wing with the OSH4 airfoil. Testing for the phugoid requires very smooth air and the characteristics have not yet been tied to any particular configuration or flight condition. It is annoying but easily controlled.

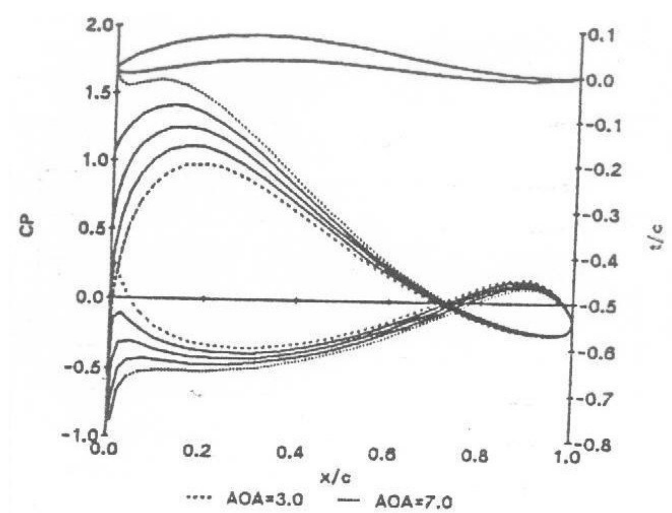


Fig. 4 Pressure coefficient OSH4 airfoil.

One of the first experiments after establishing a flyable baseline model was to try to identify the effects of various tip feather shapes and airfoils. The prototype model had a double laminated feather structure in an attempt to keep the elastic axis well forward and avoid flutter on individual feathers. The original airfoil at the tip was an extension of the double surface wing extension (Fig. 3). Some of the different wing tip feather configurations that were flown are shown in Fig. 8. The results of these tests showed no noticeable difference in the lateral stability or controllability due to the wing tip shape. Most configurations were eventually tested on only one wing to try to amplify any differences. *(ed. - On one flight the Raven accidentally hit the Telemaster on launch and knocked off one set of tip feathers. The glider flew almost normally and was recovered without any other damage.)* As the tip feathers go simpler and flatter the glide appeared to improve very slightly so the final configuration was a simple flat surface with an outline shape similar to the Raven photos.

As mentioned above the early flights of the model exhibited an undamped lateral oscillation. A reduction in the roll and yaw moments of inertia of 10% provided a noticeable increase in damping. The roll and yaw inertia with the OSH4 wing were 30% lower than the prototype and the lateral oscillation was heavily damped. To attempt to explain this oscillation a very rudimentary analysis of the Dutch roll characteristics of the configuration was attempted. The static lateral-directional stability of the Raven was analyzed by developing simplified equations for the rolling and yawing moments produced when the wing was in a sideslip. It was assumed that there were no contributions to static lateral-directional stability from the fuselage or horizontal tail. An elliptical spanwise lift distribution was assumed and lift was normalized to weight and span. The drag on each spanwise element was assumed to be related to the lift on that element by the overall L/D ratio. The change in lift on each element due to the effect of local dihedral and sweep were assessed.

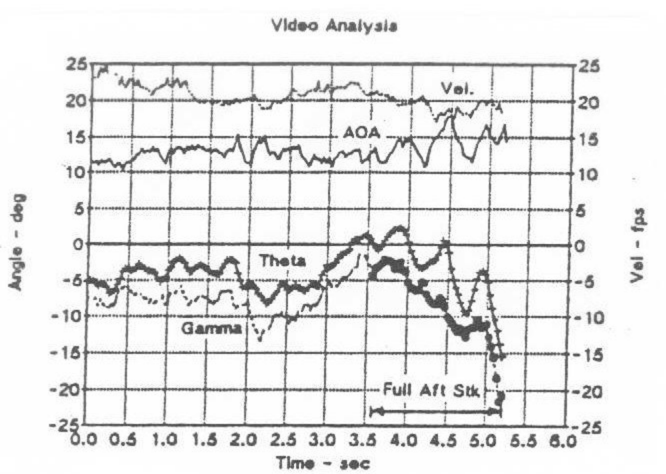


Fig. 5 Landing Time History

The change in lift due to wing sweep was assumed to be related to the change in the width of the element normal to the free stream (essentially an incremental change in area). Wing sweep at the 1/4 chord was approximated as 1/2 of the leading edge sweep angle. The total rolling and yawing moment were computed by multiplying the change in lift and drag at each element by the spanwise distance to the element. The inboard 2/3rds of the wing is influenced solely by the effects of sweep. The forward sweep of the inboard segment produces a slight destabilizing effect while the aft sweep outboard produces a stabilizing influence. The outboard 1/3 of the wing has both sweep and dihedral which produces a noticeable stabilizing effect.

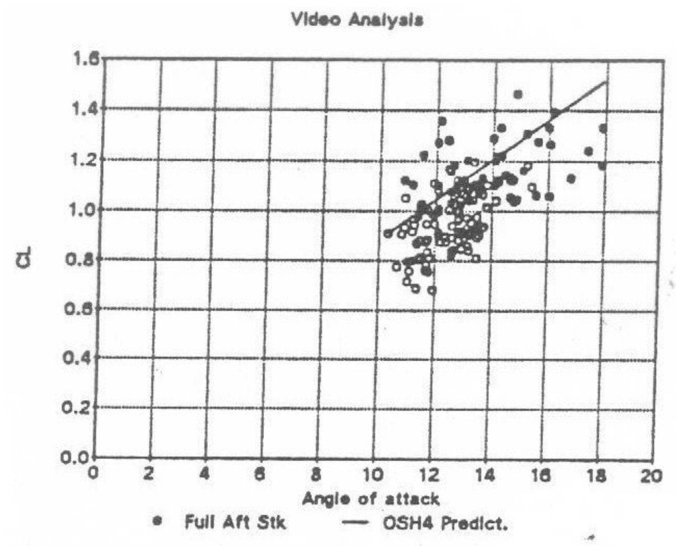


Fig. 6 Lift Coefficient

These calculations produced a value of 3.71 seconds for the early, heavy wing configuration as compared to an observed period of 3.25 seconds. Again this was considered reasonable correlation considering the simplistic approach to the analysis. It is interesting to note that the observed period is shorter than that calculated implying an even higher level of static stability than estimated. It is also possible that the observed oscillation is not a pure Dutch roll, but rather a coupled roll-spiral or some other more complex mode associated with very low levels of yaw static stability and damping, and very high levels of roll damping.

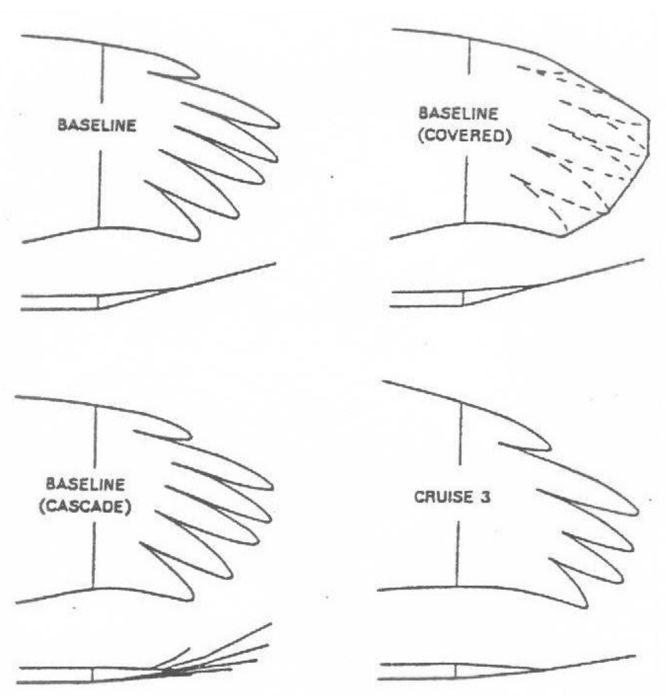


Fig. 8 Tip Feather Configuration

Following the dihedral/wing sweep tests the "rolling tail" which was described earlier was installed on the model with the CR3 wing configuration (Fig. 2). The drag flaps were retained as a backup control method.

The effectiveness of the rolling tail in yawing and turning the model depended on the lift load on the tail in trimmed flight. For a forward CG the tail was loaded downward (Fig.15a). Rotating the tail clockwise produced a left force at the tail and dihedral effect caused a right turn. For an aft CG the tail was loaded upward and the same clockwise tail rotation produced a right force, thus a left turn (Fig. 15b).

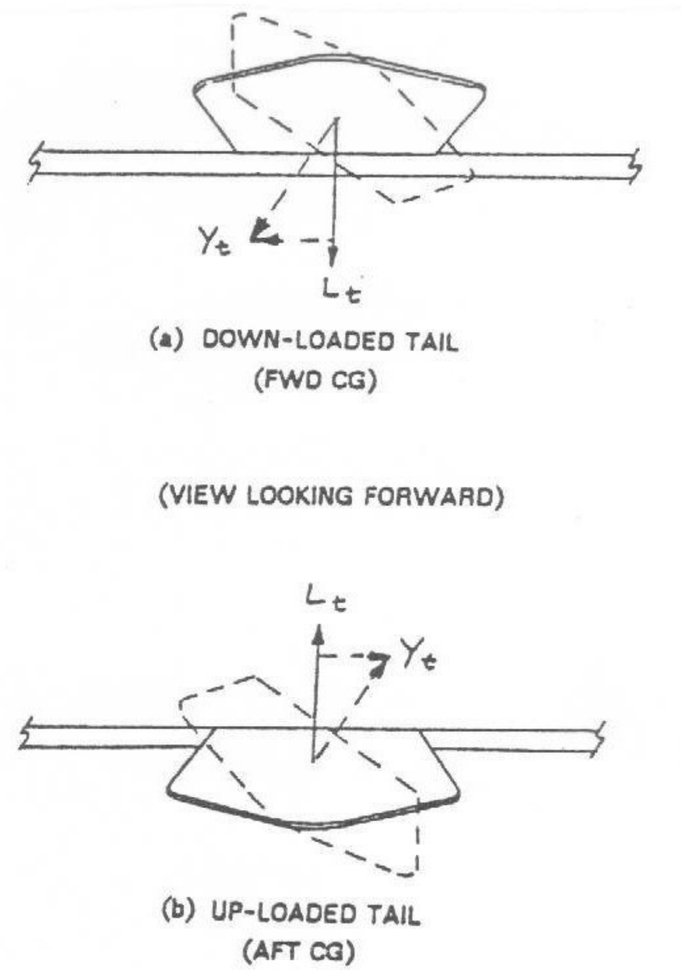
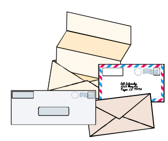


Fig. 15 Influence of tail lift on turn direction.

Initial flights were with a forward CG and the model could be turned smoothly and easily by merely rolling the tail. The model would turn in the direction that the tail was tilted. This is consistent with a forward CG and the downloaded tail of Fig. 15a. As the CG was moved aft on successive flights the ability to turn by rolling the tail diminished although turns could still be produced by combining roll and pitch commands. At the most aft CG tested the rolling tail control was reversed and the model would turn away from the direction of tail tilt. This is consistent with the up-loaded tail of Fig. 15b. Trailing-edge-down elevator deflections were also observed after landing for these flights. Several flights were completed in this configuration using only the rolling tail for pitch and yaw control. Although flying the model required constant attention in pitch, the observed tail activity was very similar to that observed on actual Ravens in soaring flight. The handling qualities were not very comfortable for a human pilot but they are probably completely normal to a Raven. It is likely that, with the on-board sensors and control effectors available to a Raven, he frequently flies with negative static margins. His handling quality requirements are substantially different than those of a human pilot responding only to external visual cues.

Now that a simple and flyable test vehicle has been developed which emulates the flight of a soaring bird a whole array of potential experiments comes to mind. Certainly the planform/dihedral equations for lateral-directional stability should be tested against the wing shapes of other bird species such as the Pelican, Hawk, Buzzard and Albatross. The results presented here must be considered preliminary and applicable only in the realm of soaring flight.

(ed. - This ends the portion where Bob has described the initial tests and laid the ground work for putting on moveable "feathers" on the wing tips to control the "bird". Next month we will continue with part two and go into "how they did that". Bob can be reached via e-mail at: bobh@patprojects.org)



LETTERS TO THE EDITOR

11/15/99

TWITT:

Please renew me. I flew with Bernhard Mattlener, the test pilot of the PUL-10, in a Cessna 150 to renew his American pilot's license. By his count, the PUL-10 is much easier to fly than this factory built tailed aircraft. We hope soon to be working on the PUL-10 in America and I look forward to being checked out in this flying wing.

Barney Vincelette

(ed. - Thanks for the renewal and the brief snippet on the PUL-10. I didn't realize you were getting close to importing parts for a prototype development plane here in the US. When you have more time could be fill in some of the blanks and let us know how the tandem design has worked out and the potential for kits in the future.)

11/17/99

TWITT:

Let me thank you for a further year of sending the very informing TWITT Newsletter - your very good work for all enthusiasts in the flying wing community.

I am including my renewal for another year since I was in Florida and able to get a check in US funds which was much easier than last year.

Wishing you all the best for the millennium and I will enjoy hearing from TWITT further good news in the New Year.

With best regards,

Rudolf Storck
Deisenhofen, Germany

(ed. - Thanks for the renewal and we hope you enjoy next year's issues as much as those of the past.. We keep trying to make it better as time goes by, but member feedback is very important to know we are on the right track.)

11/22/99

TWITT:

I talked with the Horten builder yesterday and took a closer look. The last prototype built (??) before the war was a large twin jet. It was never flown, because as the allied forces invaded Germany it was destroyed.

This project was built from the plans for that wing. The allowable gross for this wing when completed is 16,000 lbs. It is designed for supersonic flight. Two seats tandem. Construction is 1/8" plywood skin over wing ribs spaced about 13" apart. All joints use an expanding urethane glue which has been extensively tested. Initial power for flight testing will be a 454 Chevrolet engine and propeller. Fuel capacity will be about 500 gallons. With 450 square foot of area that is about 35 lb/ft at gross weight. At empty weight of about 4000 lbs (estimated), flying weight could be less than 8,000 lbs with full fuel and pilots. Or less than 18 lb/ft with a range in the order of 40 hours or more with the Chevrolet engine at about 200 mph (2300 rpm). The wing itself is a blended shape. The only straight lines are the leading edges of each wing. The 32 degree sweep is not the same as used in other Horten wings nor is the 2.5 degree twist. The aspect ratio is about 4:1. Inboard there are 2 sets of flaps. The innermost deflect a maximum of 15 degrees down. the outer set deflect 12 degrees. The outer set are used as trimmers and can also deflect upward when the inner flaps are deflecting down for use as airbrakes. Separately there is also a set of spoilers for turning or glidepath control. Dr. Horten had some problems with ground effect taking some previous designs off the end of the runway without the use of spoilers and airbrakes.

The plans the builder is working from are in his home and are of 1/2 view about 1/4 scale in size. About 6 or 7 feet long. He also has a full size root rib hanging on the wall.

At this time he doesn't want visitors other than myself. He is a commercial pilot and feels that the numerous people who want to visit would interfere too much with his limited building time.

The current plan is to move the Horten from his house to the airport for final assembly and testing in about a month when all the skins are on . People can then view it and take pictures at the airport. The plan further calls for first flights in about 6 months.

Phil Rendahl

(ed. - Phil is not a member, so I'm not quite sure how he came across our organization, but we are glad he did and felt compelled to write us about this project. We can certainly respect the builders desire for privacy at this point in time and wish him well in getting it airborne safely. I will follow up with Phil in February or March to see how the project has progressed if I haven't heard from him first. I will let you know what I find out.)

FUNDAMENTALS OF SAILPLANE DESIGN

By Fred Thomas

A Book Review by Bruce Carmichael

Rejoice! Thanks to the dedicated six-year translation effort by aeronautical engineer and glider pilot Judah Milgram, Dr. Thomas' book is now available in English. This most complete and popular text on the subject, available in German since 1979, has in addition been updated for this 3rd edition by Judah Milgram and a host of top contributors in the field, well known by the readers of OSTIV and Technical Soaring. Mathematics is kept to a minimum with physical understanding emphasized verbally plus visually with clear illustrations. Basic equations are presented, but derivations are left to other texts. A valuable bibliography is provided with many references readily available in the OSTIV publications.

The scope is very broad, starting with the basic fluid dynamics involved in understanding lift and drag. The principle characteristics of the boundary layer and separation phenomena are covered. Airfoil geometry, coefficients, design, and history are followed by discussions of wing planforms, lift distributions and stalling characteristics. Drag polar and performance equations are given, followed by discussions of static and dynamic stability and controllability. Brief descriptions of both static and dynamic aeroelasticity are also included.

Analytical modeling of cross country flight optimization using thermal velocity distributions ranging from the 1954 models of this reviewer to the 1976 Horstmann models (more characteristic of measured European thermals) is given in some detail.

Design optimization through choice of aspect ratio, wing loading, airfoil, wing planform and twist is followed by coverage of winglets, variable geometry and tailless designs. The latest development of World Class and the "eta" 101-foot span super sailplane illustrates two distinct design objectives.

Reductions in parasite drag are shown through the evolution of minimum drag fuselages, the difficult wing-fuselage interference problem and empennage and control design including all flying tails.

Performance polar calculations and wind tunnel and flight verification discussions are followed with polars of many modern sailplanes. A written and pictorial history of sailplane development from pre-WW II wooden types to the Eppler/Nagele Phoenix, which marked the beginning of the composite era, to the Standard, Racing and Open Class ships of today, is presented together with tables of design data and drawings.

This book represents the most complete single reference on the development of the world's most efficient manned flying device. The 3 pound, 9 by 11 by 1 inch hard cover beauty may be obtained from the College Park Press, P.O. Box 143, College Park, MD 20741, ISBN 0-9669553-0-7 for $56 incl. postage with 20%/30% off for 5/10 copies. Check or major credit card through website http://www.cgpp.com.

MY PROPELLER THEORY

By E. Eugene Larrabee, Prof. em, MIT
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In 1978 I developed a useful form of propeller theory based on the work of Hermann Glauert (1926 and 1938) and Sidney Goldstein (1929). It was successfully applied to the propellers of the Gossamer Albatross and Chrysalis human powered airplanes in 1979 and (in reverse) to windmills for US Windpower, Inc. in 1980.

It is related to lifting line theory as developed by Ludwig Prandtl and his associates at Göttingen during WW I. In it an induced velocity is developed parallel to the blade lift direction and perpendicular to the relative velocity of the blade section with respect to the air mass. The flight (or axial) velocity, the rotational velocity, and the induced velocity combine to produce the resultant velocity. The induced velocity is caused by lift on each blade section due to bound circulation according to the Kutta-Joukowski Law.

Strangely enough if the induced velocity is small enough compared to the axial velocity it can be shown that the induced loss of the propeller is minimized if the virtual slip velocity is radially constant, corresponding to a certain radial variation of the bound circulation. As Albert Betz, Prandtl's associate, said in 1923 (NACA TR 116), "The flow behind the propeller having the least loss of energy is as if the screw surfaces passed over by the propeller were solidified into a solid figure and this were displaced backward in the non-viscous fluid with a given small velocity". The small displacement velocity is exactly twice the virtual slip velocity.

I calculated the radial bound circulation distributions for minimum induced loss by a process suggested by Glauert in 1938. The distributions are functions of the advance ratio and the number of blades. They correspond to elliptic span loading for a wing.

Apparently these circulation distributions are slightly in error as suggested by Goldstein in 1929 and by my former student, Mark Drela, in 1982. In any event, they were good enough to form the basis of a Fortran code written by Hyong Bang in 1978 to define the blade chord and pitch angles for the Gossamer Albatross and Chrysalis airplanes, so that they had not only minimum induced loss but also minimum profile drag by choice of blade section and lift coefficient at the design point. They "were propellers of highest efficiency" in Glauert's words.

At the relatively low advance ratios of these propellers they are characterized by narrow outer blade chords and wide inboard ones with strong twist, having almost true geometric pitch.

The same is true of the US Windpower windmills generated by a later Fortran code HELICE, written by Susan Elso French at MIT. In the case of windmills the displacement velocity is against the wind direction and the more curved portions of the blades are downwind. They were intended to leave a minimum hole in the air for a given power output for the average wind speed of a "windfarm" of many windmills.

Since then Prof. Mark Drela has developed his own XROTOR code which is a finite element adaptation of Goldstein's 1929 paper. XROTOR was used to design propellers for the Monarch and Daedalus airplanes. French's HELICE code was rewritten in Pascal as ELICA by Robert S. Grimes in a form suitable for IBM personal computers in 1982. Both Prof. Ernst Schöberl and I have used ELIA for many years. I published my algorithms in 1980.

I am told that Aerovironment uses a form of them to design propellers for their airplanes including the Pathfinder, which holds the altitude record for propeller driven airplanes.